The Stellar Consensus Protocol (SCP)

draft-mazieres-dinrg-scp-05

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Motivation: Internet-level consensus

Atomically transact across incompatible/distrustful systems

- E.g., Transfer domain name in exchange for payment

Irrevocably delegate identifiers

- E.g., certify email user public key w/o ability to equivocate

Verify public disclosure & timestamp of information

- Build IoT device that only upgrades to public firmware

All of these can be addressed w. public append-only log

Slice infrastructures

A *slice infrastructure* is a set of *nodes* that select *quorum slices*

Each node picks quorum slices it believes speaks for the Internet

- E.g., I pick {Stanford, IETF}, you pick {Baidu, Wechat, Alibaba}
- Alibaba and Stanford both include Google in their quorum slices
- Transitively, we both depend on Google
- Want guaranteed agreement so long as Google honest

For fault tolerance, pick multiple quorum slices

- E.g., 4/5 FAANG companies, or 3/4 of servers from each FAANG

Define quorums as the transitive closure of slices

- Let $\mathbf{V}$ be all nodes, $\mathbf{Q}(v)$ be all of node v's quorum slices

Definition (Quorum)

A quorum $U \subseteq \mathbf{V}$ is a set of nodes that contains at least one slice of each of its members: $\forall v \in U, \exists q \in \mathbf{Q}(v)$ such that $q \subseteq U$

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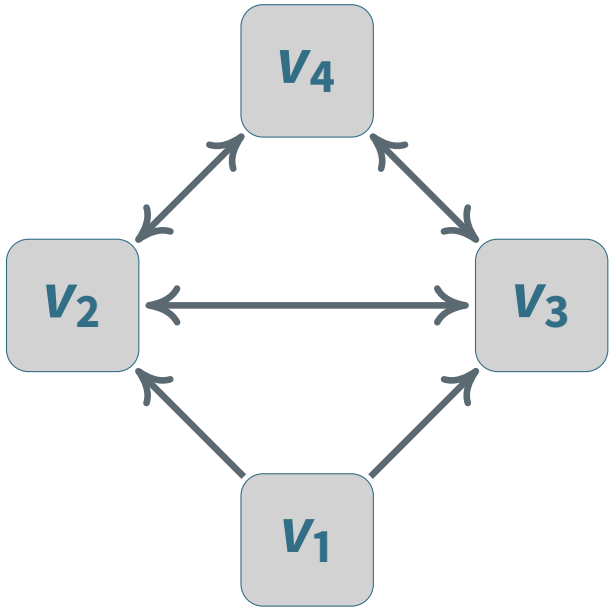

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Visualize quorum slice dependencies with arrows

v_2, v_3, v_4 **is a quorum—contains a slice of each member**

v_1, v_2, v_3 **is a slice for** v_1**, but not a quorum**

- Doesn't contain a slice for v_2, v_3, who demand v_4's agreement

$v_1, \ldots, v_4$ **is the smallest quorum containing** v_1

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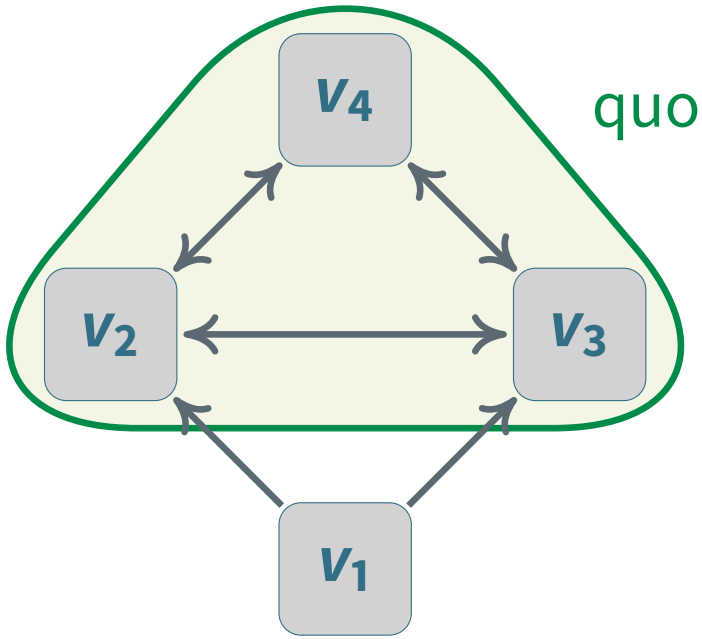

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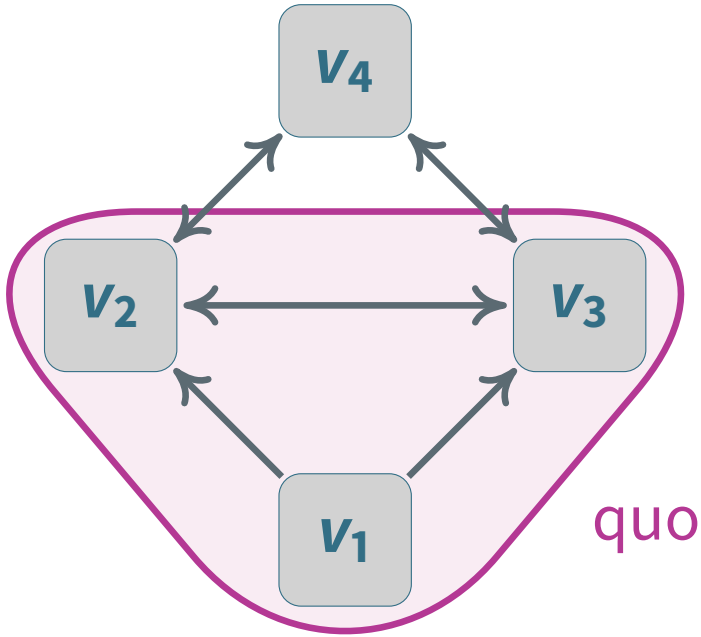

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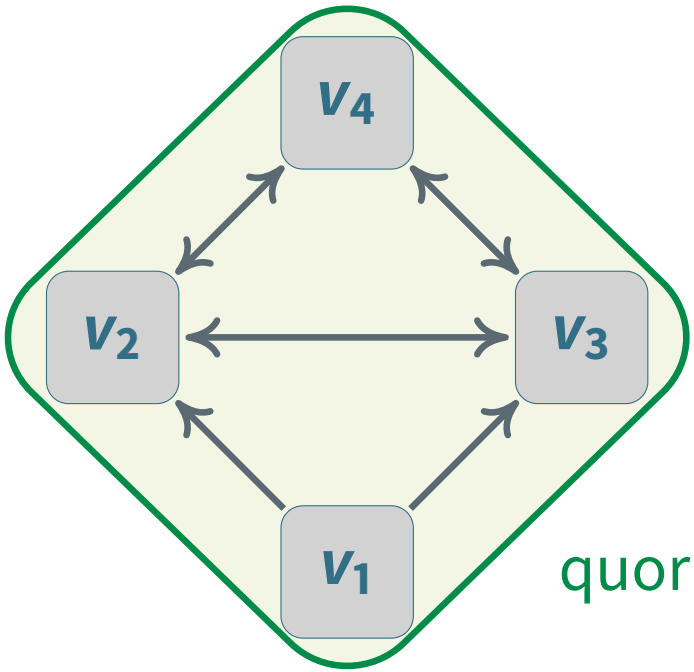

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Two important thresholds

A node *v* believes message *m* reaches...

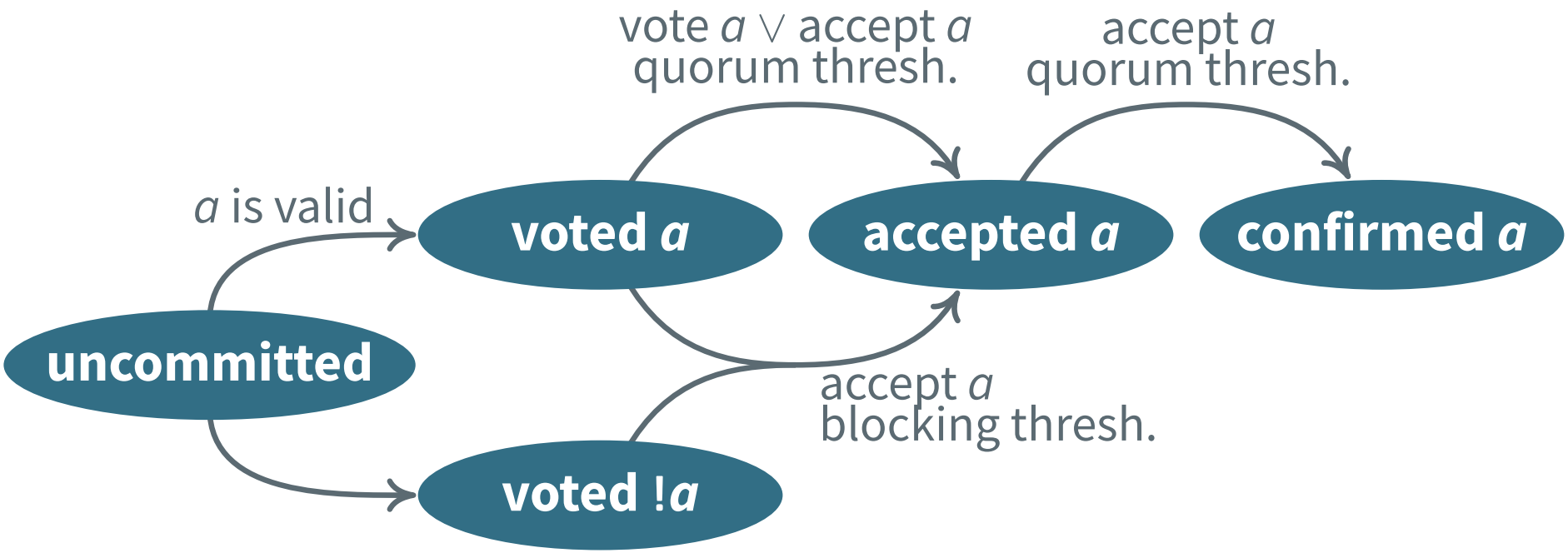
Quorum threshold – when a quorum including *v* all sends *m*

- Note *v* doesn't care about quorums it doesn't belong to (maybe Sybils)

Blocking threshold – a node sent *m* in each of *v*'s quorum slices

- Means if *v* in any honest quorum, none of its quorums can contradict *m*

Main subroutine: federated voting



Nodes vote for or against a conceptual statement *a*

- Illegal to vote for or accept two contradictory statements
- But you can vote for one statement then accept a contradictory one

When you confirm a statement, you know

- If you are *intact*, all other intact nodes will eventually confirm it
- Nodes *intertwined* with you won't confirm contradictory statements

Until you confirm a statement, it might get permanently stuck

SCP overview by phase

NOMINATE – pick some value to try to agree on

- Nodes will likely agree if network synchronous, but can disagree

PREPARE part 1 – confirm prepare(b) for ballot $\langle b.\texttt{counter}, b.\texttt{value}\rangle$

- Use federated voting to abort and commit ballots
- prepare(b) $= \{\, \text{abort}(b') \mid b' < b \ \wedge\ b'.\texttt{value} \neq b.\texttt{value} \,\}$
- b.value taken from nomination output until any ballot p is confirmed prepared, then use $p.\texttt{value}$ for highest confirmed prepared ballot p

PREPARE part 2 – accept commit(b) after confirming prepare(b)

- But if in the process you accept abort(b), go back to PREPARE part 1

COMMIT – confirm commit(b) after accepting

EXTERNALIZE – output value of confirmed committed ballot

- Also send message to optimize quorum discovery for slower nodes

Ballots details

```
struct SCPBallot {
  uint32 counter;
  Value value;
};
```

Ballots totally ordered with `counter` more significant than `value`

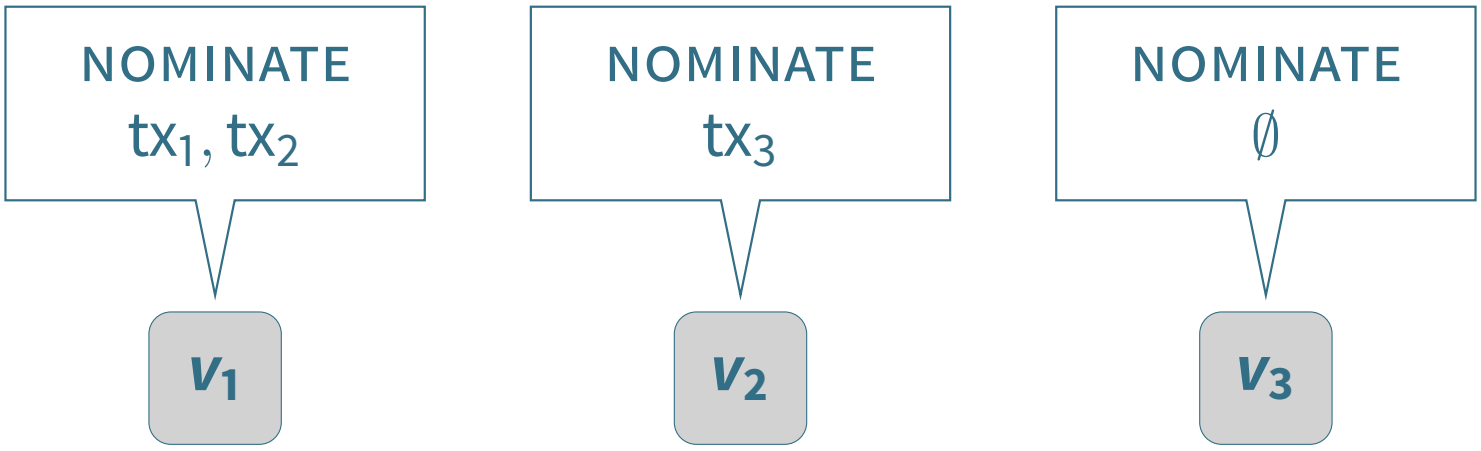
If a node confirms commit(b) for any b, it decides b.`value`

Recall prepare(b) = $\{$abort(b') $\mid b' < b \ \wedge \ b'.\texttt{value} \neq b.\texttt{value}\}$

Key invariants

- A node may vote abort(b) or commit(b) but not both (contradictory)
- A node may accept abort(b) or commit(b) but not both
- A node cannot vote commit(b) unless it first confirms prepare(b)
  $\Longrightarrow$ all committed & stuck ballots have same value

Nomination flow



Nodes nominate values and re-nominate any nominations seen

Stop adding to `votes` once any value confirmed nominated

Will converge on set of values

Deterministically combine nominations into *composite* value x

Nodes guaranteed to converge on same value x

- Complication: impossible to know when protocol has converged [FLP]

NOMINATE overlaps PREPARE to continue in background

- Ends when ballot confirmed prepared, as all intact nodes will confirm prepared ballot and use its value

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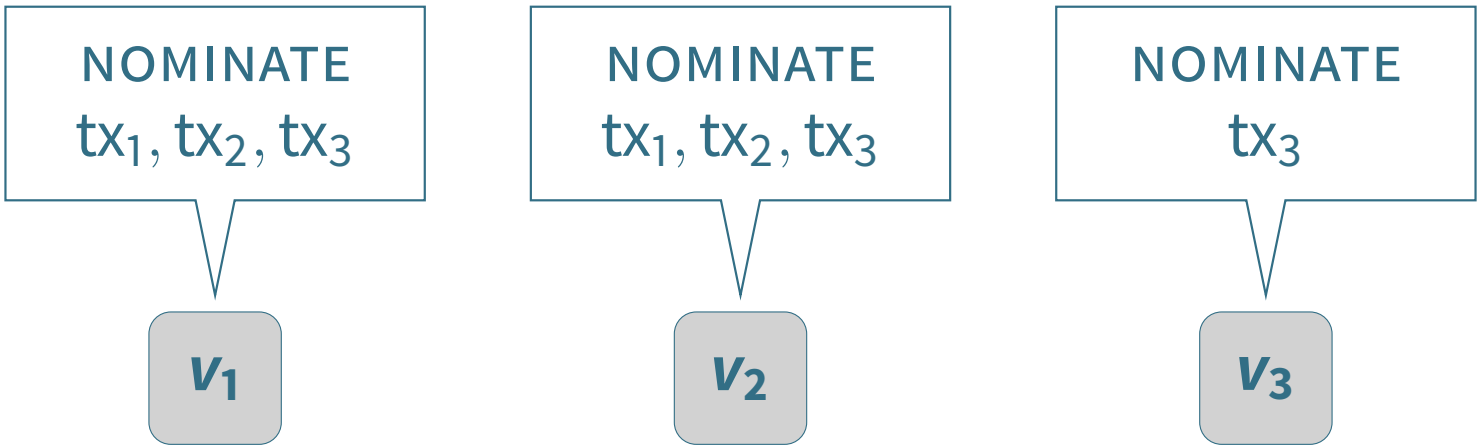

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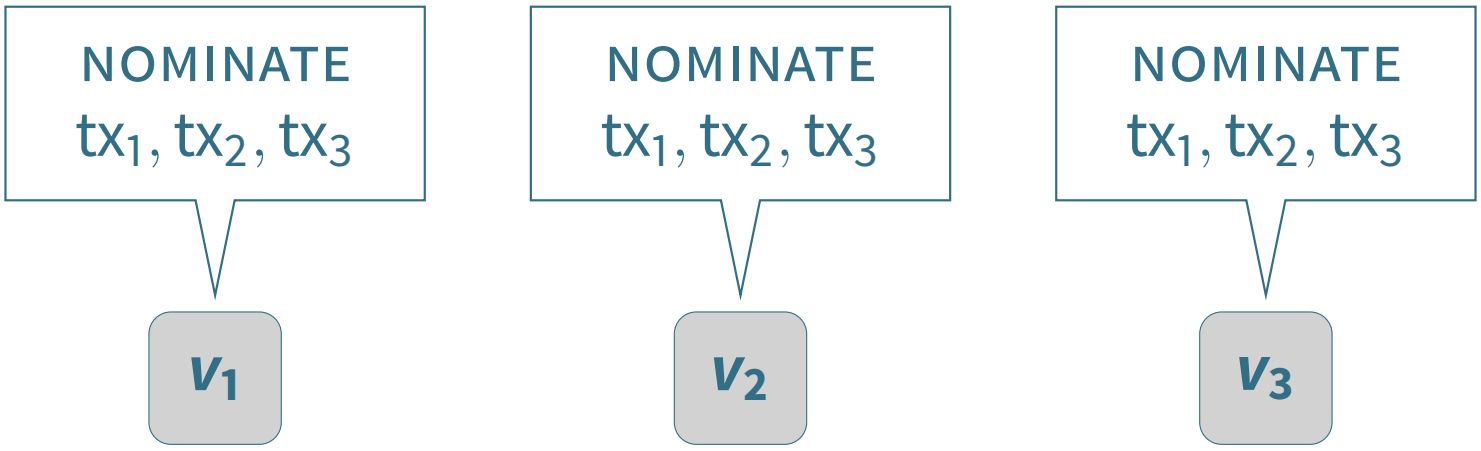

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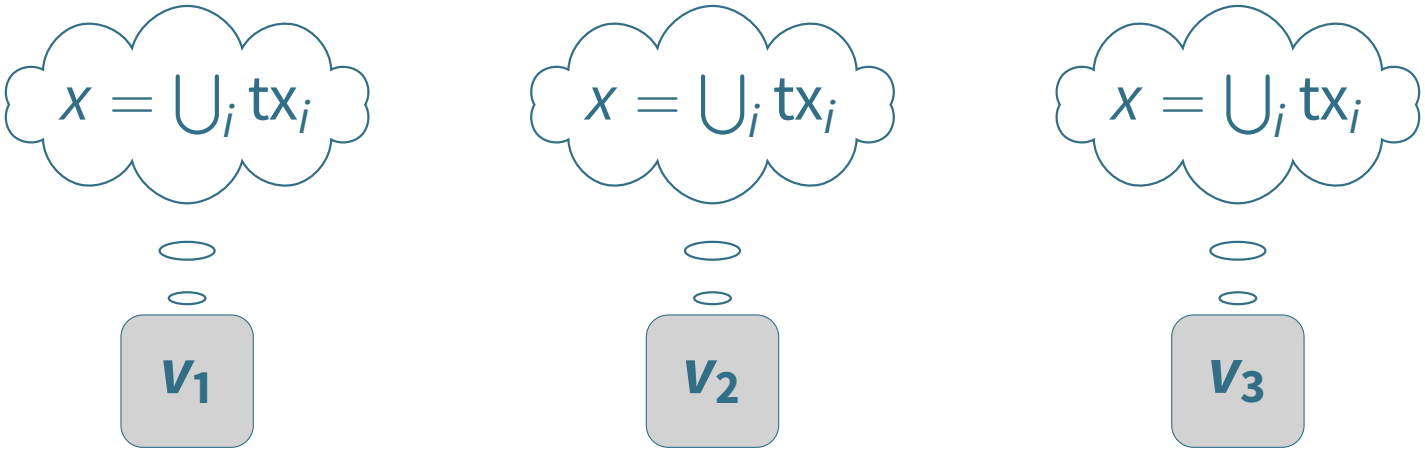

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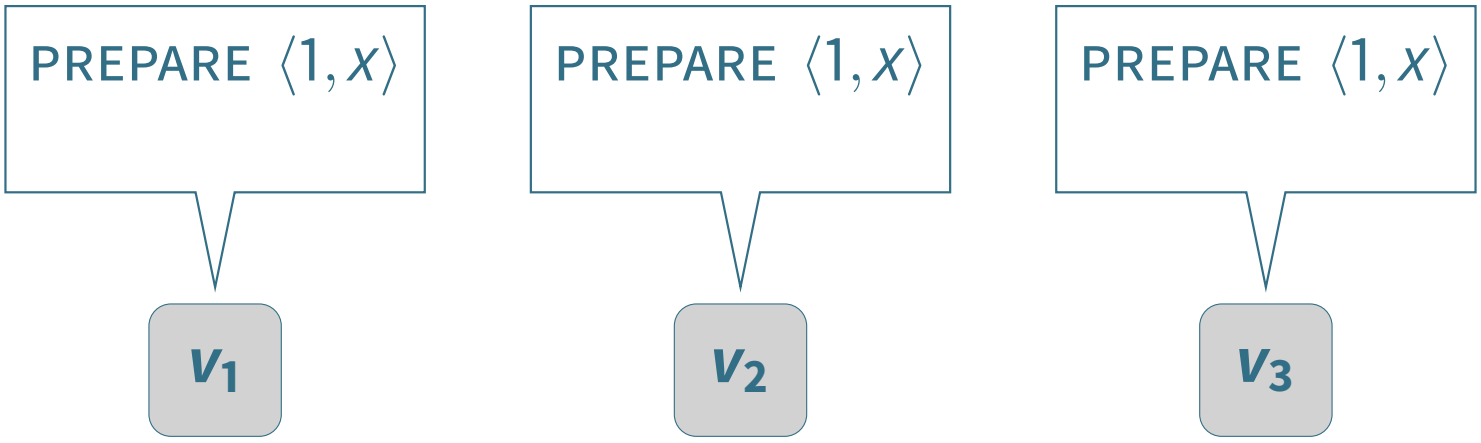

In the common case, will prepare and commit nominated value

Else, arm timer when ballot counter reaches quorum threshold

Bump counter and restart with new ballot whenever

- Timer fires
- A blocking threshold is at a higher ballot counter

Timeout lengthens as counter increases

- Intact nodes spend longer and long on same counter together
- Eventually emulates a synchronous system

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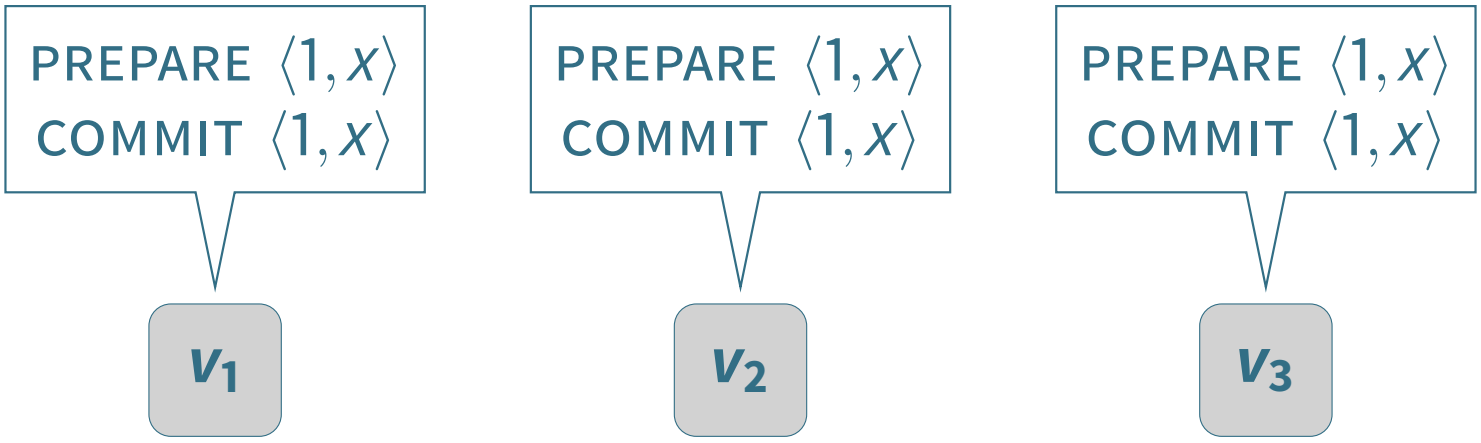

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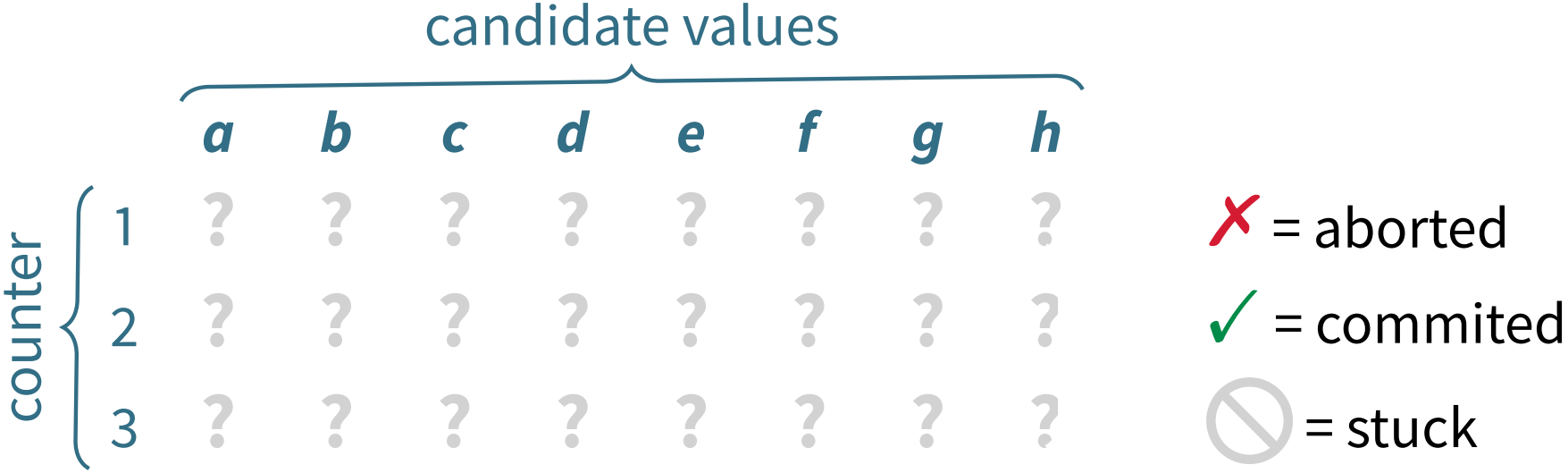

0. **Initially, all ballots are bivalent**
1. **Prepare $\langle 1, g \rangle$ and vote to commit it**
2. **Lose vote on $\langle 1, g \rangle$; agree $\langle 2, f \rangle$ prepared and vote to commit it**
3. **$\langle 2, f \rangle$ is stuck, so agree $\langle 3, f \rangle$ prepared and vote to commit it**
4. **Confirm commit $\langle 3, f \rangle$ and externalize f**
   - At this point nobody cares that $\langle 2, f \rangle$ is stuck

Notice how all committed & stuck ballots have same value

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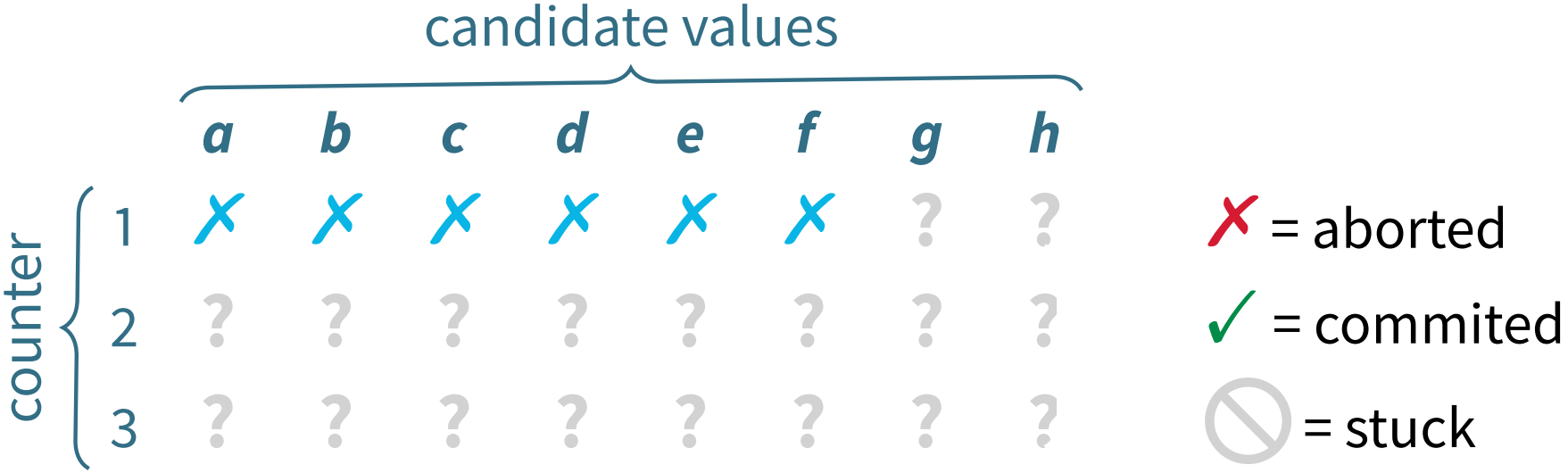

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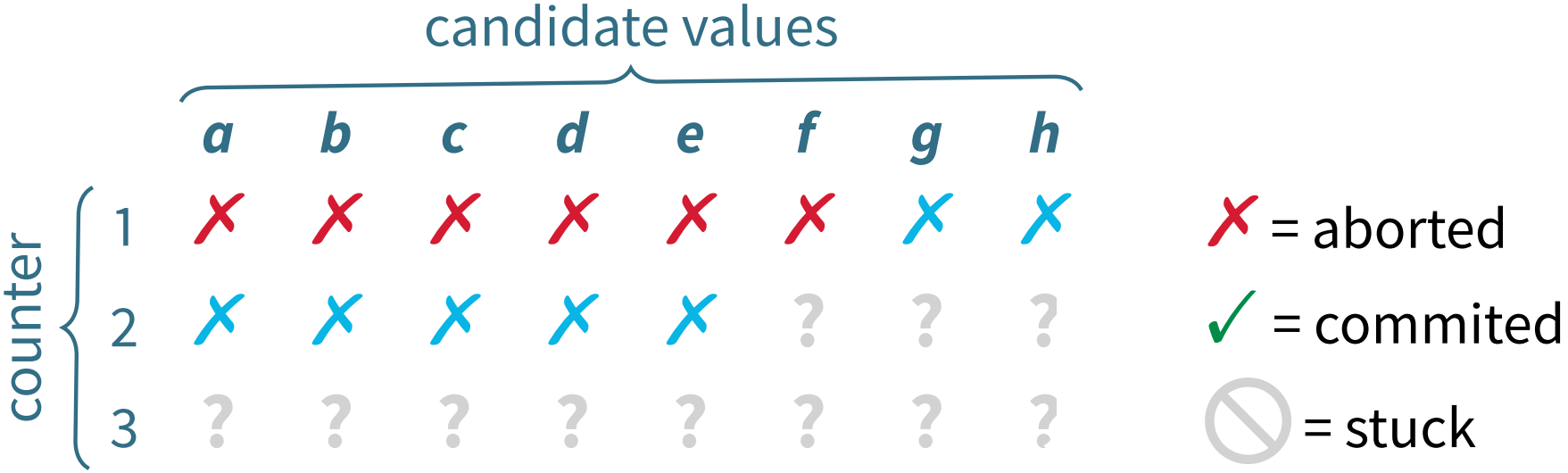

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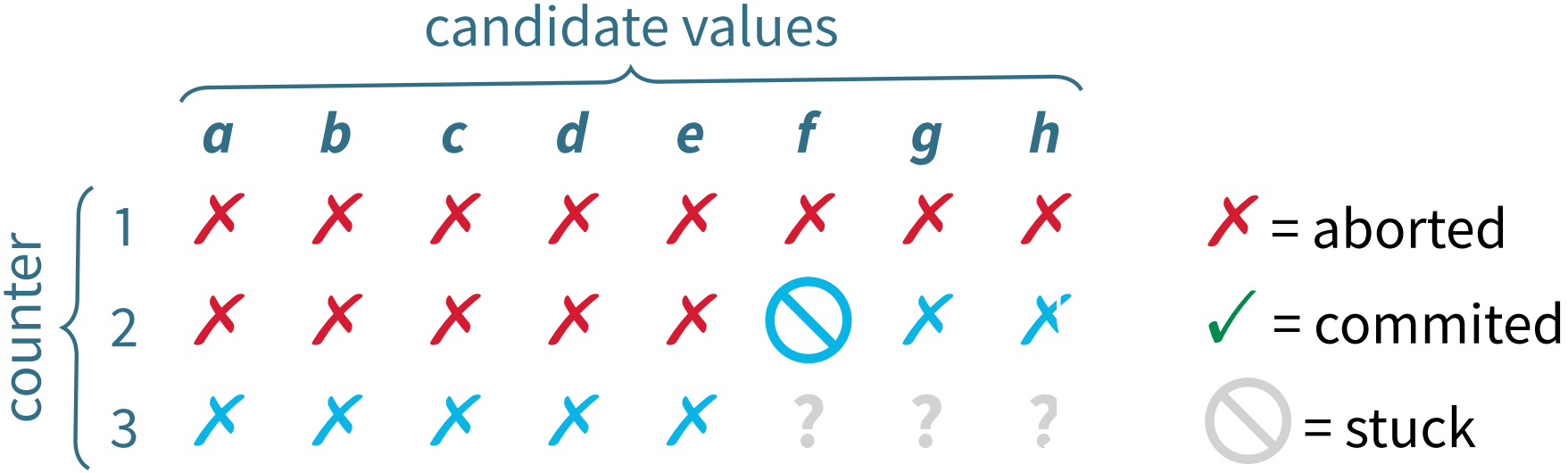

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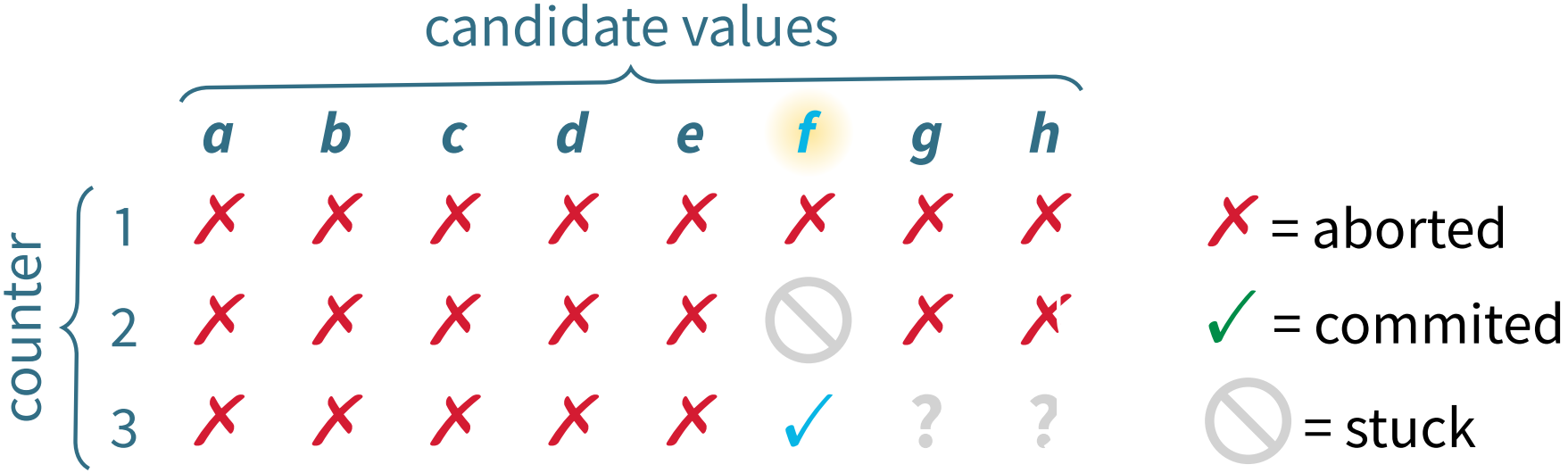

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SCP prepare message (changed)

```
struct SCPPrepare {
  SCPBallot ballot;
  SCPBallot *prepared;
  uint32 aCounter;     // new -- replaces preparedPrime
  uint32 hCounter;
  uint32 cCounter;
};
```

vote-or-accept prepare(`ballot`)

if `prepared` $\neq$ **NULL: accept prepare**(`*prepared`)

accept $\{$ **abort**(b) $\mid$ b.`counter` $<$ `aCounter` $\}$

if hCounter $\neq 0$**: confirm prepare**($\langle$**hCounter**, **ballot.value**$\rangle$)

if cCounter $\neq 0$**:**
vote $\{$**commit**($\langle n,$ **ballot.value**$\rangle$) $\mid$ **cCounter** $\leq n \leq$ **hCounter**$\}$

Progress to COMMIT phase upon accepting commit(b) **for any** b

Setting the prepare fields

`ballot.counter` starts at 1, increases with timeouts/blocking sets

`ballot.value` b.`value` from highest confirmed prepare(b) (if any), else composite nomination value (if any), else b.`value` from highest accepted prepare(b) (if any), otherwise don't send `SCPPrepare` yet

`prepared` highest b for which sender accepted prepared(b)

`aCounter` `counter` (or `counter` +1) of highest accepted prepared ballot with different value from `prepared.value`

`hCounter` h.counter from highest h with confirmed prepared(h) and b.`value` $==$ h.`value` (new), else 0

`cCounter` 0 if `hCounter` $==$ 0 or internal "commit ballot" c $==$ `NULL`. Else, c.counter. Note $c \leftarrow$ `ballot` when confirmed prepared and `NULL` when accepted aborted.

Status

The good news

- Draft is stabilizing (one open question: max nomination message size)
- Existing protocol has slightly better liveness than previously proven
- At least 4 implementations: stellar-core, Bob Glickstein, Mobilecoin, Peirs Poslesland

The bad news – might want huge changes / other documents

- No hope of interoperability because no multicast specification
- Maybe we can improve liveness by re-running nomination between counters (would terminate with prob. 1 even with Byzantine nodes)
- Maybe simpler protocol for slice infrastructures (would require alternate competing draft, slow everything down)

Questions?

SCP nomination message

```
typedef opaque Value<>;

struct SCPNominate {
  Value voted<>;     // vote to nominate these values
  Value accepted<>;  // assert that these are accepted
};

union SCPStatement switch (SCPStatementType type) {
  case SCP_ST_NOMINATE:
    SCPNominate nominate;
  /* ... */
};
```

Nodes broadcast nominated values in `voted`

- Initially vote values in all received votes (ignoring optimization here)

Upon accepting nomination of a**, move from** `voted` **to** `accepted`

Stop voting for new values once any is confirmed nominated

- But continue accepting and repeating votes already cast

Stop sending `SCPNominate` **when ballot confirmed prepared**

- Means NOMINATION phase overlaps with PREPARE phase

SCP commit message

```
struct SCPCommit {
    SCPBallot ballot;
    uint32 preparedCounter;
    uint32 hCounter;
    uint32 cCounter;
};
```

$\{$**accept commit**$(\langle n, \texttt{ballot.value}\rangle) \mid \texttt{cCounter} \leq n \leq \texttt{hCounter}\}$

vote-or-accept prepare$(\langle \infty, \texttt{ballot.value}\rangle)$

accept prepare$(\langle \texttt{preparedCounter}, \texttt{ballot.value}\rangle)$

confirm prepare$(\langle \texttt{hCounter}, \texttt{ballot.value}\rangle)$

$\{$**vote commit**$(\langle n, \texttt{ballot.value}\rangle) \mid n \geq \texttt{cCounter}\}$

SCP externalize message

```
struct SCPExternalize {
    SCPBallot commit;
    uint32 hCounter;
};
```

$\{\textbf{accept commit}(\langle n, \texttt{commit.value}\rangle) \mid n \geq \texttt{commit.counter}\}$

$\{\textbf{confirm commit}(\langle n, \texttt{commit.value}\rangle) \mid \texttt{commit.counter} \leq n \leq \texttt{hCounter}\}$

$\textbf{accept prepare}(\langle \infty, \texttt{commit.value}\rangle)$

$\textbf{confirm prepare}(\langle \texttt{hCounter}, \texttt{commit.value}\rangle)$

By the time you send this, already externalized `commit.value`

- Means you have confirmed committed a ballot with `commit.`*value*
- Goal is definitive record to help other nodes prove value/catch up